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13. ABSTRACT (Maximum 200 words)

We have successfully transferred MOCVD processes for producing high quality AlN epilayer templates, which were developed in our home-built growth system, to production scale systems with 6 pieces of 2-inch wafer capability. We consider this a critical step, as this capability enables us to have an ample supply of templates to make multiple runs per day, which is necessary for the development of growth processes for green LD structures. Furthermore, we have significantly improved the crystalline quality of these AlN epitemplates, as evidenced by a decrease in the FWHM of the XRD rocking curve of the asymmetric (102) reflection peak from greater than 400 arcsec to below 300 arc.

We have successfully evolved our green light emitting diode (LED) structure to 500 nm LD structure by inserting cladding and light guiding layers. We have obtained a significant improvement in optical emission efficiency by depositing the emitter structures on AlN templates (see report)

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Enclosure 1

Final Report

Award No: 53412-EL-DRP

Project Title: AlInGaN bandgap and doping engineering for visible laser diodes

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I. Summary of Progress

Background

There is a great need to develop chip-scale visible lasers for many applications, including laser sight, environmental monitoring, and compact pumping sources for ultra-short laser pulse generation, high luminous full color displays, new generation solid-state lighting, etc. The realization of chip-scale visible laser diodes (LDs) would provide significant benefits in terms of cost, volume, and the ability of photonic integration with other functional devices.

Significant progress in nitride material technology has been achieved and high performance visible LEDs and near UV LDs based on InGaN are now commercially available. However, many technological challenges remain to be overcome in order to realize InGaN visible injection LDs. The two most outstanding issues are (i) high dislocation density which causes a premature device breakdown and (ii) low conductivity (or doping efficiency) of p-type GaN, which limits an efficient current injection. The objective of the proposed research is to develop improved growth and doping methods for achieving GaN and AlInGaN alloys with improved crystalline quality and conductivity and to aid in the development of III-nitride visible injection LDs operating at around 500 nm.

Accomplished Milestones

MOCVD growth

Our technical approaches include the use of high quality thick AlN template as a dislocation filter to reduce the parasitic conduction and trapping density in the device structure and to minimize the leakage current and premature breakdown.

- We have successfully transferred MOCVD processes for producing high quality AlN epilayer templates, which were developed in our home-built growth system, to production scale systems with 6 pieces of 2-inch wafer capability. We consider this a critical step, as this capability enables us to have an ample supply of templates to make multiple runs per day, which is necessary for the development of growth processes for green LD structures. Furthermore, we have significantly improved the crystalline quality of these AlN epi-templates, as evidenced by a decrease in the FWHM of the XRD rocking curve of the asymmetric (102) reflection peak from greater than 400 arcsec to below 300 arc.

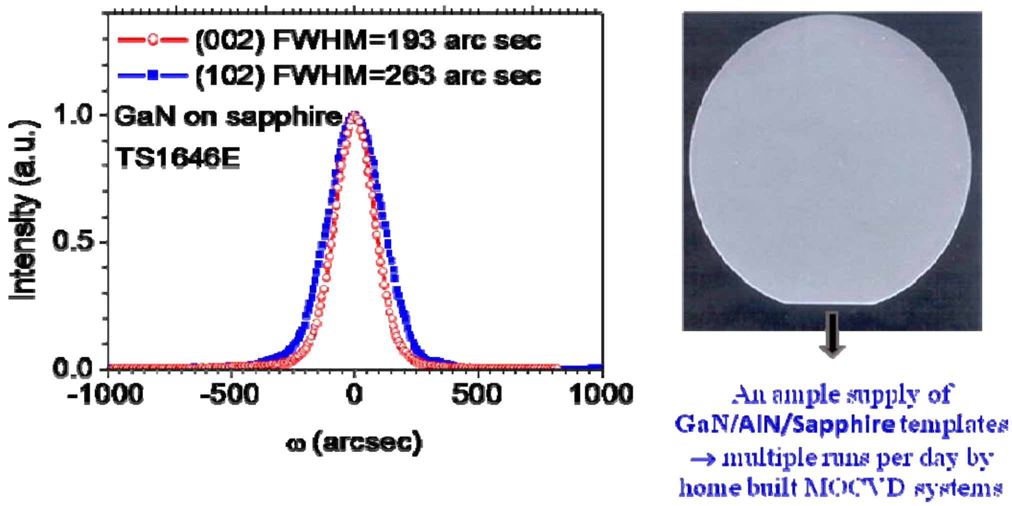

Figure description: We have successfully transferred growth receipt of AlN epi-templates from home-built MOCVD system to production scale MOCVD system and improved the overall crystalline quality of AlN epi-templates.

- We have successfully evolved our green light emitting diode (LED) structure to 500 nm LD structure by inserting cladding and light guiding layers. We have obtained a significant improvement in optical emission efficiency by depositing the emitter structures on AlN templates.

- We have also carried out preliminary studies of MOCVD growth of GaN epilayers and LD structures on bulk GaN substrates synthesized by HVPE. Compared to LD structures grown on AlN/sapphire templates, LD structures grown on GaN bulk substrates exhibit lower dislocation density (narrower XRD and EL emission spectra linewidth) and comparable output optical power.

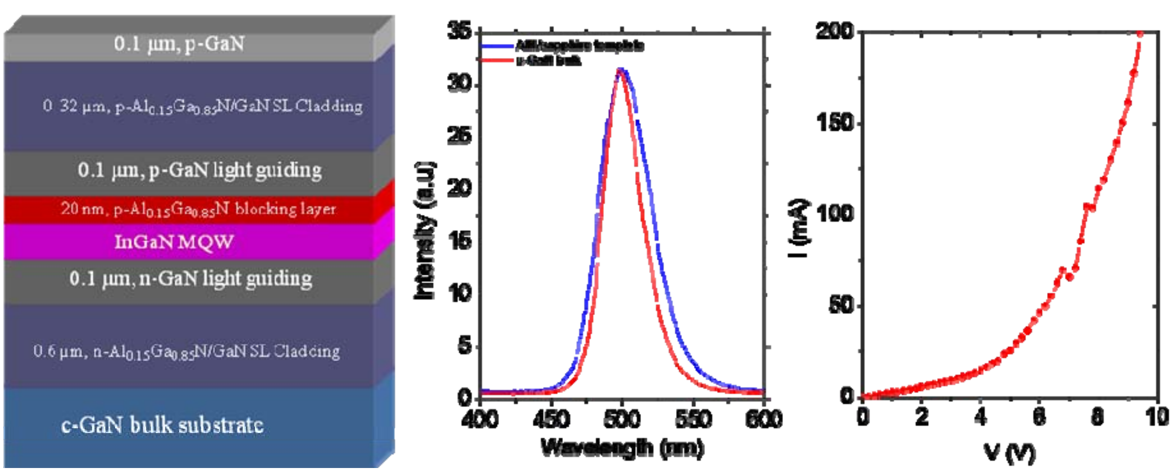

Figure description: (Left) LD structure grown n c-plane GaN bulk substrate; (Middle) EL spectra of LDs grown on AlN/sapphire template vs. on c-bulk GaN; (Right) I-V characteristics of LD on c-GaN bulk.

- $In_xGa_{1-x}N$, It has been exceedingly difficult to obtain homogeneous composition control and high quality InGaN materials in the middle indium composition range, 0.45 < x < 0.75. There are only limited studies to address the MOCVD growth of the InGaN epilayer system in the entire composition range. Furthermore, detailed studies concerning the optical and transport properties of $In_xGa_{1-x}N$ in the miscibility gap region (0.45 < x < 0.75) have not been possible due to the fact that these $In_xGa_{1-x}N$ films generally are of very low crystalline quality and exhibit negligible PL emission. Our preliminary results have shown that by directly depositing on GaN or AlN epi-templates without buffer layers, InGaN epilayers of the entire alloy range without phase separation could be produced by MOCVD.

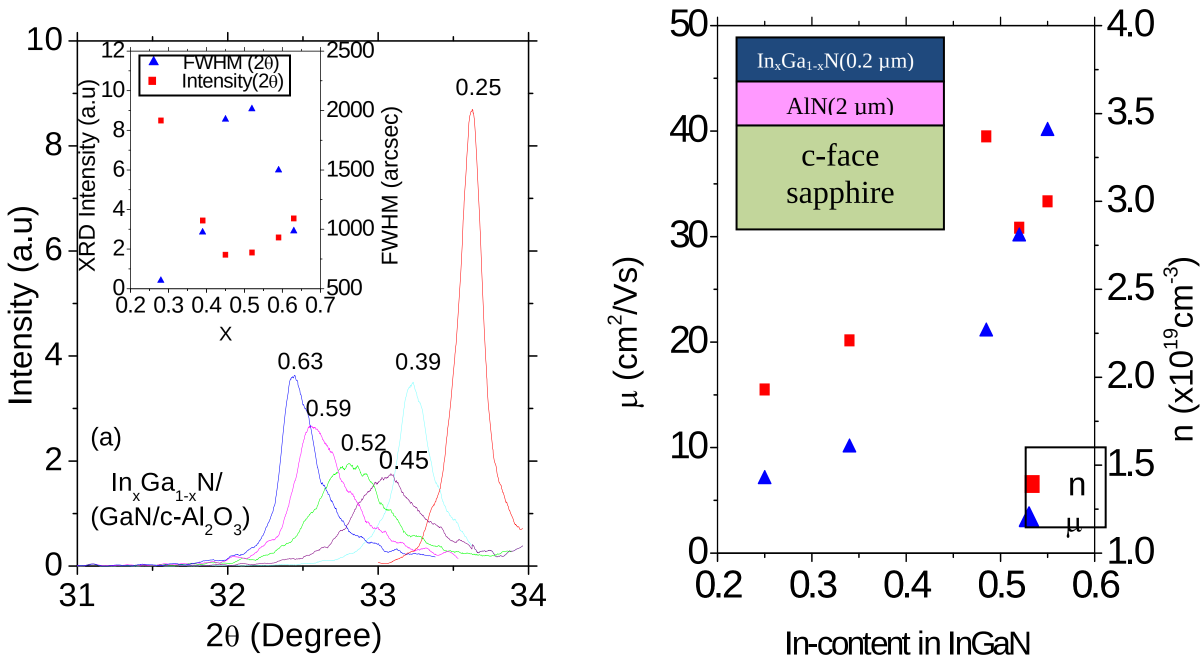

Figure description: XRD spectra of θ-2θ scans of (002) plane of $In_xGa_{1-x}N$ grown on c-GaN/c-Al_2O_3 templates. The inset shows the XRD FWHM and relative intensity as functions of In-content. (b) Electron concentration and mobility of $In_xGa_{1-x}N$ epilayers grown on c-AlN/Al_2O_3 templates as function of x. All curves, scanned down to InN peak position, have no multiple peaks, which implies that InGaN alloys are not phase separated. The reason for the increase in μ with increasing In-content could be the lower effective mass of the electrons. The measured 300 K electron mobility of $In_{0.55}Ga_{0.45}N$ alloys is about 40 cm^2/Vs and of pure InN is as high as 1400 cm^2/Vs.

The attainment of single phase InGaN alloys inside the previously thought miscibility gap by MOCVD may be attributed to the following factors:

- the presence of biaxial strain between the InGaN thin film and the GaN or AlN epi-template,
- non-equilibrium growth processes taking place in epitaxial growth techniques like MOCVD,
- relatively low growth temperatures (The growth temperature varied from 730 to 610^{o}C as the In-content was increased from 25% to 63%).

LD device design, fabrication, and characterization

- Ridge waveguides with 5 to 20 µm widths and 500 to 1500 µm lengths were fabricated. We have also developed a method for preparing the laser cavity by controlled mechanical polishing. The polished laser facets has a root-mean-square surface roughness of ~ 0.5 nm over a 10 µm x 10 µm scanning area as probed by AFM.

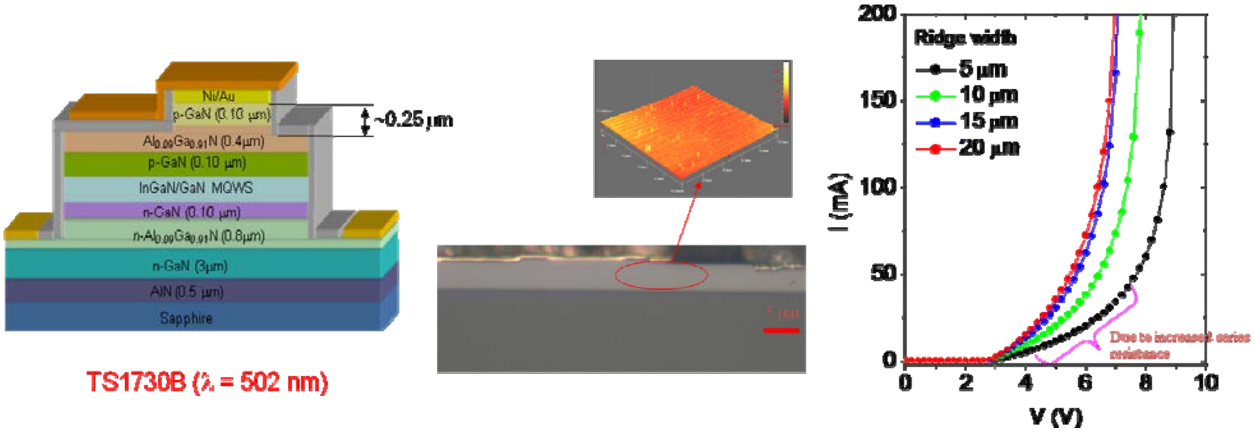

Figure description: (Left) Schematic diagram of fabricated ridge waveguide laser. (Middle) Optical microscopy image of cross-section of ridge waveguide laser. The laser facets were prepared by slow and controlled polishing. AFM scan over polished surface of 10 mm x 10 mm area showed rms ~ 0.5 nm. (Right) I-V characteristics of fabricated LDs, indicating that the operating voltage increases with decreasing ridge width and further improvement in device processing is necessary.

- We are also developing the processes for obtaining ¼ wave reflectors for 500 nm operation based on SiO_2/TiO_2 multi-layers for the laser cavity to minimize the optical loss.

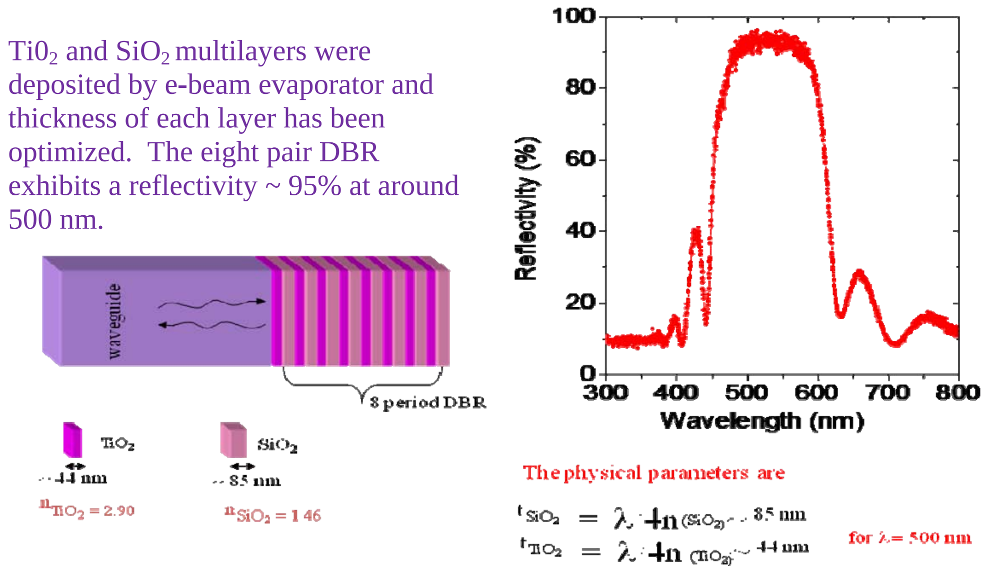

Figure description: Highly reflective TiO_2/SiO_2 dielectric multilayer coating for green laser has been developed.

Although lasing at 500 nm has not yet been observed, the work accomplished in the first funding period laid the ground work for achieving 500 nm LDs within the proposed project period.

II. Publications:

1. B. N. Pantha, R. Dahal, M. L. Nakarmi, N. Nepal, J. Li, J. Y. Lin, H. X. Jiang, Q. S. Paduano, and David Weyburne, “Correlation between optoelectronic and structural properties and epilayer thickness of AlN,” Appl. Phys. Lett. 90, 241101 (2007).

2. Z. Y. Fan, J. Y. Lin, and H. X. Jiang, “III-nitride micro-emitter arrays: development and applications,” Special Issue, J. Phys. D: Appl. Phys. 41 094001 (2008).

3. T. M. Al tahtamouni, A. Sedhain, J. Y. Lin, and H. X. Jiang, “Growth and optical properties of a-plane AlN and quantum wells grown on r-plane sapphire substrates,” Proceedings of ICNS-7, phys. status solidi (c) 5, 1568 (2008).

Principal investigators have been honored by Texas Tech University and offered the esteemed positions of Edward E. Whitacre, Jr. Endowed Chair and Linda F. Whitacre Endowed Chair in Nanophotonics (Mr. Whitacre is the former CEO of AT & T).